CHAPTER TWELVE

Crowd management solutions

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Abstract

Crowd management can provide an intermediate solution for the short-term to pressing crowd safety concerns at limited costs. It entails the systematic process of planning, organizing, and monitoring large gatherings of people to establish and maintain a safe and secure environment. This chapter provides a toolbox that planners and crowd managers can use to identify crowd incident risks, design crowd management strategies, and develop crowd management systems. In addition, some practical pointers concerning the operationalization of crowd management strategies are provided and several future challenges are highlighted.

1. A brief introduction to crowd management

According to experts in crowd management, the number of large-scale crowd management operations is rising. At the same time, they identify that the complexity of the 'average' crowd management operation is also increasing due to the increasing size of the crowd, complex population mixtures, and densely populated built environments not designed to handle large, dense crowds. In addition, crowd management operations take place in pedestrian spaces that are not solely used by people who are the target of the crowd management operation but also by individuals with a different goal in mind. For instance, train stations are not only used by people who need to catch a train but also by people who need to cross the train tracks or need to buy something in the stores that are located at the train station. This mixed use of pedestrian spaces further complicates crowd management operations as 'daily life' should be able to continue as much as possible. Consequently, concerns regarding the safety of pedestrians frequently arise.

Previous chapters have identified a myriad of characteristics of the person, the crowd in general, and its built environment that can be leveraged to improve the safety of crowds. For instance, dynamic signage can serve as a short-term intervention to redirect (a part of) a crowd to a less popular walking route. At the same time, the redesign of the street network could, in a few years, improve the overall movement patterns of citizens in a neighborhood, thus rendering the dynamic signage unnecessary. Yet, any thorough redesign costs time and budget, which are often difficult to secure.

Crowd management can provide an intermediate solution for the short-term to pressing crowd safety concerns at limited costs. Crowd management is defined by the author as "*the set of all potential crowd management* *interventions one can pre-emptively design and prepare to limit the crowds' safety risks while moving towards, circulating in or moving away from a public space*". It entails the systematic process of planning, organizing, and monitoring large gatherings of people to establish and maintain a safe and secure environment. When performed correctly, crowd management operations reduce and mitigate the risks associated with potential crowd incidents way in advance. Given its focus on crowd safety, one often encounters crowd management operations in public spaces during large-scale events, such as music concerts, demonstrations, festivals, sports stadiums, and theme parks.

Please note that this definition of crowd management is slightly broader than some other definitions of this term (e.g., Street Solutions UK, 2025; Software, 2025; FSSBV, 2025) To untangle the inherent confusion between the intertwined definitions of 'crowd management', 'crowd control', and 'riot control', we will also provide a definition for the latter two. In the remainder of this chapter, crowd control is defined as the '*reactive response to unforeseen crowd dynamics to limit the crowds' safety risks while moving towards, circulating in, or moving away from a public space*.' Riot control is defined as the "*measures used by law enforcement, military, paramilitary or security forces to control, disperse, and arrest people who are involved in a riot, unlawful demonstration or unlawful protest*." (Wikipedia Contributors, 2025). Consequently, the main difference between crowd management and crowd control is in the pro-active nature of crowd management and reactive nature of crowd control. The main difference between crowd control and riot control is the entity that needs to take action. In the case of crowd control, the crowd managers of the public space are in charge, while in the case of riot control, law enforcement organizations support the crowd management organization or take over completely. In the remainder of this chapter, we will focus solely on crowd management operations, as the proactive design and planning of potential crowd management interventions form the backbone of any safe pedestrian infrastructure.

The previous chapter has scoured the literature to determine which factors impact pedestrians' decision behavior and movement dynamics. As such, chapter 11 has identified a variety of opportunities to use interventions to steer pedestrians individually or as a crowd. Yet, to manage a crowd, knowing that light can be used to nudge pedestrians' choice behavior is insufficient (e.g., van Beek et al., 2024). We must know when and where to apply which crowd management interventions to steer the crowd proactively. Not surprisingly, the answer depends on the context of the crowd management case. For instance, a crowd management operation in a venue that is designed to accommodate large crowds, such as a stadium, theme park, or shopping mall, has different requirements than a crowd management operation in an urban area that was initially designed for day-to-day travel. Thus, instead of directly answering the When, Where, and How questions in this chapter, it is more informative to provide a toolbox that one can use time and time again to derive these three answers for each specific context.

Consequently, this chapter aims to provide practical guidelines for designing effective crowd management solutions. When used in unison, these guidelines answer the when, where, and how questions formulated above. These guidelines comprise three parts: (1) crowd risk identification and assessment methods, (2) guidelines to design crowd management interventions, and (3) methods to automate crowd monitoring and management. The first element we will use to identify when and where crowd dynamics in public spaces might potentially pose risks. The second element supports the design of targeted interventions and provides guidance regarding how to intervene when potential crowd incident risks arise. The last element aids the design and operationalization of proactive crowd monitoring schemes that can help continuously and objectively monitor the most significant crowd incident risks. Fig. 1 provides a visualization of the interconnections between the elements.

The following Section 2 will first introduce a crowd risk identification and assessment metrics framework. Section 3 presents the golden principles to design crowd management interventions. Accordingly, Section 4 introduces the control loop for crowd management, which describes the foundation of crowd management systems. Section 5 provides some suggestions regarding the practical implementation of digital support systems for a large-scale crowd management operation. Section 6 presents an outlook into the future of public space management. Section 7 closes this chapter with a synthesis.

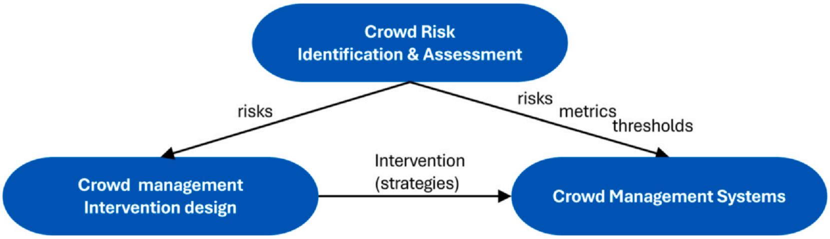

Fig. 1 Connection between the three elements.

2. Crowd risk identification and assessment methods

The first tools in the toolbox are the Crowd Safety Risk Identification (CRI) and DIM-ICE frameworks. Both of these can be used to unravel potential crowd incident risks systematically and will be introduced in Sections 2.2 and 2.3. When all risks are identified, ordering is required. Section 2.4 will present guidelines that facilitate the systematic ordering of crowd incident risks. Section 2.5 closes this chapter with the presentation of guidelines featuring the quantification of crowd incident risks, an essential step to track crowd incident risks during the design and operational phase of pedestrian infrastructures. Before doing so, we must first define crowd safety and risks in Section 2.1. These definitions will allow us to better identify the relevant risks in the second part of this section.

2.1 Defining crowd safety and crowd risks

Oxford Learner's Dictionary defines safety as "the state of being safe and protected from danger or harm" (Oxford English Dictionary (2025)). We can extend this definition to crowd safety: "Crowd safety is any state of the crowd, during which it is safe and protected from danger or harm."

This definition is still inconclusive. To measure crowd safety accurately, we must specify what exactly constitutes danger or harm. In a crowd, danger or harm to individuals is caused by events including falling, fainting, or being trapped between people, objects, or infrastructure (e.g., Nicholson and Roebuck, 1995; Helbing and Mukerji, 2012; Yang et al., 2024). These are instances indicative of loss of physical control and/or loss of consciousness and could lead to personal injuries, such as blunt trauma, musculoskeletal trauma, and compressive/traumatic asphyxia, which, in the worst case, leads to death. Hence, we've defined crowd safety as "people not being exposed to conditions in a crowd where they could lose physical control and/or lose consciousness." In essence, crowd safety is a Boolean value. It is either 'safe' or 'not safe'.

It is often difficult to establish precisely when a situation moves from being safe to being unsafe. Therefore, in engineering and planning, a slightly different formulation is usually adopted, namely 'crowd incident risk'. According to the Fine-Kinney method, risk is the product of (1) the probability that a crowd incident will occur, (2) the frequency that an incident occurs, and (3) the size of the impact (also called effect) of a crowd incident (Kinney and Wiruth, 1976). Here, the *incident probability* is often quantified using a continuous value between 0 (i.e., incidents are never happening) and

1 (i.e., incidents are occurring all the time). An incident probability of 0.1 resembles a 10 % probability that a crowd incident will occur under given circumstances. For instance, the probability that flow break occurs increases with density and population heterogeneity (Campanella et al., 2009). The incident frequency quantifies how often an incident is expected to take place. The expected incident frequency of overcrowding at a large train station is probably higher than that of an overcrowding event at your local supermarket. The *incident effect size* is quantified using a wide variety of metrics, among which are the number of casualties, number of injured individuals, delay time, and highest experienced density level (e.g., Nicholson and Roebuck, 1995; Helbing and Mukerji, 2012; Bruijl, 2022). In Section 2.5, guidelines are provided regarding which risk quantification metrics to adopt to monitor particular crowd incident risks.

2.2 Crowd risk identification framework

Using the concept of crowd incident risk. van Schaik et al. (2024) has drafted a Crowd Risk Identification framework (van Schaik et al., 2024). The framework aims to help understand how (historic or hypothetical) crowd incidents evolve by structuring relevant information. Ideally, it helps identify critical conditions that may lead to a crowd incident. Knowledge regarding the events leading up to a crowd incident can be used to anticipate (the risk of) crowd incidents during the planning phase and/or the crowd management operation. The goal of CRI framework is to develop a comprehensive list of potential crowd incident risks for a given pedestrian infrastructure, without yet determining the crowd incident probability, frequency, and effect.

The framework's structure (see Fig. 2) is quite simple and comprises four parts:

- **Adverse environmental conditions:** The conditions leading up to the adverse crowd condition phase. These are often contextual conditions

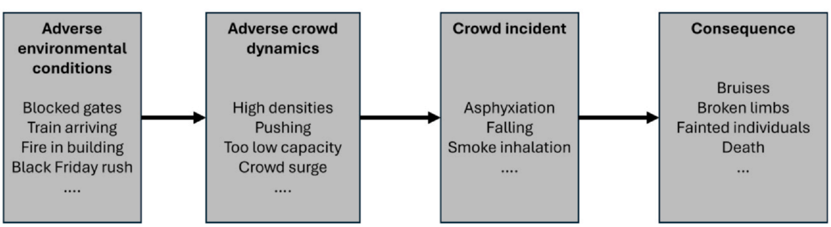

Fig. 2 Visualization of crowd risk identification framework.

that create sudden shifts in pedestrian demand, pedestrian goal-orientation, infrastructure availability and/or environmental conditions. For example, the arrival of a full train at a platform loaded with passengers or sudden heavy rain shower during a city marathon.

- **Adverse crowd conditions:** The conditions inside the crowd leading up to the crowd incident. As a result of the adverse environmental conditions, sudden changes in the crowd's choice behavior and dynamics occur. This element describes exactly how the crowd's goal-orientation, choice behavior, and movement dynamics change locally and globally.
- **Crowd incident:** A crowd incident occurs when one or more individuals lose control (e.g., by falling or not being able to control their movements anymore), are unable to recover, and thus face the consequences (e.g., injury).
- **Consequences of incident:** The physical consequences for any individual in the crowd directly resulting from the incident.

Similar to the preliminary version presented by (van Schaik et al., 2024), one can use the framework to identify potential crowd incident risks in two ways. Firstly, one can start by listing the most probable adverse environmental conditions and, accordingly, reason which adverse crowd dynamics, crowd incidents, and consequences result from these environmental conditions, given that one is not proactively intervening in the scenario. One can also start by listing the crowd incidents and reason backward to identify the adverse crowd conditions and adverse environmental conditions that might potentially cause these crowd incidents. The framework aims to end up with a list of probable crowd incident scenarios for a given context.

2.3 DIM-ICE

The DIM-ICE risk model is a second framework that can be used to identify the crowd incident risks, which was developed by prof. Keith Still. The reader is referred to Still et al. (2020) for a thorough explanation of this model and several applications of the DIM-ICE model to identify crowd risks.

In essence, the DIM-ICE risk model is a technique that systematically identifies failure routes and highlights moments of high risk. Here, failure routes can be translated as crowd incident risks. This allows event organizers to deal with and control those risks through effective design, information systems, and management strategies.

The framework uses three dimensions to describe potential crowd incident risks, being: the phases of crowd behavior during an large-scale event or crowd gathering, the primary influences of the environment on crowd behavior, and the modes of crowd behavior.

The three primary phases of crowd behavior identified in the DIM-ICE strategy are:

- **Ingress** – The phase during which visitors are traveling towards the venue.
- **Circulation** – The phase during which visitors move within the venue from one activity to the next.
- **Egress** – The phase during which visitors are moving from the venue back to their homes after the event has finished.

The three primary influences on crowd behavior in the DIM-ICE strategy are:

- **Design** – This influence represents all limitations of the infrastructure design (e.g., capacity, throughput, surface stability, line of sight).
- **Information** – This influence represents all information provided to the crowd through formal and informal media. Examples are the organization's website, social media channels, news articles featuring the event, Twitter, and Instagram.
- **Management** – This influence represents all processes and procedures that are in place to manage the crowd. Including, but not limited to, the crowd management organizational chart, the various actors' responsibilities, and the number and whereabouts of all staff members.

The first two dimensions form a matrix (see Fig. 3). For all three phases of the visitor experience (e.g., ingress, circulation, and egress) and three primary influences (e.g., design, information, and management), one can identify the crowd incident risks that can potentially arise. As the crowd's behavior is expected to differ between normal and adverse crowd conditions, the matrix is often completed twice. One time featuring normal conditions and one time featuring emergency conditions.

By methodically filling all 18 cells of the two matrices, one automatically derives the main risks during each crowd behavior phase.

	Ingress	Circulation	Egress
Design			
Information			
Management			

Fig. 3 DIM-ICE framework proposed by Prof. Still Still et al. (2020).

2.4 Ordering crowd incident risks

The two Risk Identification frameworks identify potential crowd incident risks for a given context. Crowd management plans need to be drafted to mitigate those incident risks. Often, the focus is on developing sophisticated crowd interventions. Yet, one cannot mitigate all risks due to a limited supply of staff, budget, and time.

So, which ones should be focused on when designing a crowd management plan? For example, should we allocate resources to prevent the sudden influx of demand due to a sudden social-media hype or ensure an ambulance can drive through a dense crowd? A rapid increase in pedestrian demand due to a Project X party will cause crowding issues (Cohen et al., 2013). Yet, is the rapid increase in demand a probable scenario for the particular context and case to be studied at a given moment? A Project X party is, in most pedestrian infrastructures, not very probable. On the other hand, an ambulance that needs to drive through a very dense crowd in a pedestrian infrastructure might not be a frequent sight. Still, it is a highly probable scenario that someone injures him/herself in a crowd and an ambulance needs to be brought in to treat the person. Thus, we would want to add the ambulance scenario to the list of adverse environmental conditions for any public festival.

The goal of this second step is to order the potential risks so that we can prioritize the allocation of resources to mitigate the most prominent crowd incident risks. The Swiss cheese model by Reason (1990) is an accident causation model used in risk management (Reason, 1990). This model depicts human systems (including crowd management operations) as a combination of multiple slices of cheese. Here, the slices resemble the crowd management intervention strategies, each of which has its own 'flaws'. For example, ticket gates prevent people from coming into a train station without a ticket, but it will not necessarily alleviate crowd pressure on a train platform. Crowd incidents are the arrows that try to find a way through the stack of cheese slices. In theory, any weakness in the system can only materialize when the holes in all the cheese slices are aligned. That is, when none of the activated crowd management interventions mitigates a particular risk completely.

Please note that it is often impossible to completely mitigate a risk, let alone mitigate a crowd incident risk by means of one targeted intervention. Often, one can only decrease the incident probability. Layered mitigation strategies, comprised of a set of measures that partly limit one crowd incident risk, are often adopted to jointly block one of the holes. At the same time, some risks are too difficult to mitigate completely. In those cases, crowd management interventions can be aimed at limiting the incident effect size. For instance, crowd watchers located behind the stage barriers can limit the incident effect of fainting people by pulling them out of the pressure point, but they might not be able to prevent them from fainting in the first place.

The question then becomes, which risks (i.e., red arrows through the slices of cheese in Fig. 4) should definitely be mitigated? Fig. 5 provides a visualization of the relationship between incident probability and effect size. In essence, incidents with a low probability of occurring and a small effect size (i.e., lower left corner) are less essential to track than incidents with a high probability of occurring and a high effect size (i.e., top right corner). Reality is slightly more complex, as very improbable scenarios might have such a disruptive effect, such as a shooter scenario on a festival terrain, that one needs to prevent them from happening under any circumstances.

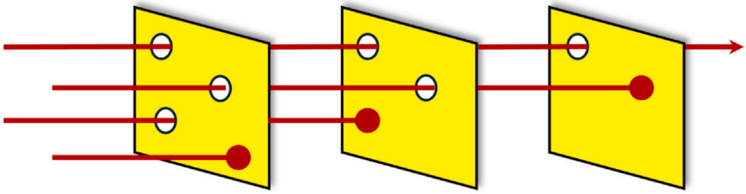

Fig. 4 Visualization of the Swiss cheese model.

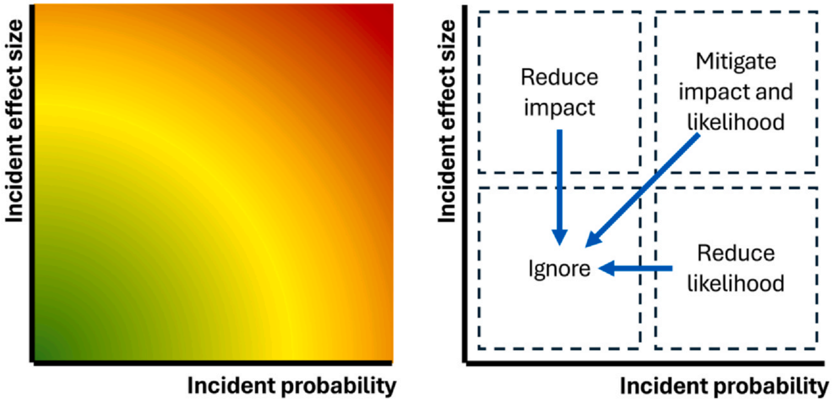

Fig. 5 Visualization of the relationship between incident probability, incident effect size, and crowd risk.

By scoring the probability and effect size of potential crowd risks, one can quickly determine which risks are essential to monitor during crowd operation. For instance, a superstorm has a considerable effect size when it occurs, but the probability that this incident will occur on a lovely spring day in May is very small. At the same time, the probability that one of the shows on an event terrain is not stopping at the negotiated time is very high, as is the potential incident effect size of 40.000 visitors running from one stage to the next to still be in time for the next show. Consequently, the latter might need to be prioritized concerning crowd monitoring and management.

Please note that during the preparation and unfolding of events on the day, the incident probabilities can shift. For instance, the weather forecast unexpectedly predicts a large thunderstorm in the afternoon. Next to changes in the size of crowd risks' incident probability, over time, the information on each of the crowd incident probabilities becomes more granular. It is essential to regularly check (and update) the incident risk probabilities to ensure one captures changes in the prominence of the crowd incident risk due to sudden changes in context.

2.5 Quantifying crowd incident risks

Effective crowd management strategies mitigate crowding risks by intervening before the crowd dynamics spin out of control. This means that risk metrics and thresholds need to be established to alert the crowd manager when the choice behavior and/or crowd movement dynamics approach the conditions under which adverse crowd conditions are more probable to occur. The result of his third step is to determine metrics and thresholds that quantify the most pressing crowd incident risks, so that we can keep an eye on them during the operation.

Using the list of adverse crowd dynamics established in the CRI framework as a starting point, relevant metrics and thresholds can be identified to monitor the crowd incident risks for a particular pedestrian space. To do so, each adverse crowd dynamics condition needs to be translated into a physical property of the crowd that can be monitored, the so-called metric or Key Performance Indicator (KPI), and a value that identifies when the adverse crowd conditions are likely to occur, the so-called threshold.

2.5.1 Metrics to quantify crowd incident risk

Metrics are properties of the crowd that can be objectively quantified using sensors and/or human crowd managers. Chapter 3 has presented an overview of sensors that can measure one or more characteristics of a

Table 1 Examples of metrics to monitor specific crowd incident risks.

Metrics	Crowd incident risk (s)
Total number of visitors	Evacuation time
Average density	Evacuation time Overcrowding according to building decree
Maximum density	Not being able to stand up when falling Development force networks Turbulence
Maximum flow rate	Flow breakdown in a corridor, entry, or exit
Maximum effective speed	Flow breakdown in a corridor, entry, or exit

crowd. In the case of crowd incident risks, we are most interested in metrics that quantify the current state of the crowd, for instance, the flow rate, density, effective walking speed, and mood. Table 1 provides a set of examples of metrics to use to monitor specific Crowd Incident Risks. Please note that the actual threshold values per metric can vary depending on the risk one is monitoring. For instance, the density at which a person cannot stand up anymore is different from the density at which forces prohibit breathing (e.g., Still, 2021; Li et al., 2020).

What is good to keep in mind is that we need properties that can quantify incident risks in real time. So, it needs to be feasible to determine the adopted metrics in real time. Various studies have shown that this is less trivial than it sounds (e.g., Wirz et al., 2012; Duives et al., 2018,2020). As organizations need time to react, it is also essential that the information on the metrics is received as quickly as possible. Coarse information regarding metrics from sensors that provide information with little latency is preferred over very granular results from sensors with substantial latency (e.g., ≥15 min). When identifying the metrics, it is essential to take into account the latency of the sensor data and the frequency at which the sensor data becomes available.

2.5.2 Thresholds of crowd incident risks

A combination of the national legislation, guidelines of event organizers and sport venues, and state-of-the-art research on crowd dynamics can be adopted to identify the thresholds. It is essential to realize that the current legislation with respect to the prevention of crowd incidents is very light. Often, only the maximum evacuation time is defined for indoor pedestrian environments. The legislation and pedestrian infrastructure design guidelines from other countries can sometimes provide a source of inspiration, for instance, (Sports Grounds Safety Authority, 2018; German Institute for Standardization, 2022; Milford et al., 2021; London Underground, 2017). In addition, one is advised to use state-of-the-art literature on crowd dynamics to identify thresholds on risks for which no current legislation or guidelines exist. Several research groups have been performing interesting work on quantifying the impact of crowd dynamics, among which (Feldmann and Adrian, 2023; Kroll et al., 2017; Moussaid et al., 2012; Campanella et al., 2009; Yang et al., 2024).

What is essential to realize is that this way of setting the threshold produces a very hard boundary condition. It is either good (low risk) or wrong (high risk). Reality is far less black and white. As mentioned before, risk is defined on a gliding scale and can, as such, be better described as a cumulative distribution function (CDF) (see Fig. 6). For instance, (Campanella et al., 2009) shows that the flow breakdown probability increases with density. In essence, a hard threshold resembles the level of incident risk that we, as a society, find acceptable while at the same time realizing that the incident probability can never be mitigated to 0.

Consequently, thresholds to curb crowd incident risks can have different values in different countries. Moreover, as the CDF of incident probability often has a steep gradient, minor differences in the thresholds of a metric can represent significant differences in the acceptance of incident probability. For instance, even though the green (- -), yellow (-.-), and blue (–) density thresholds are relatively similar and equally spaced, the accompanying incident probabilities are far apart and unequally spaced. Working with the actual CDF of a given incident probability can provide

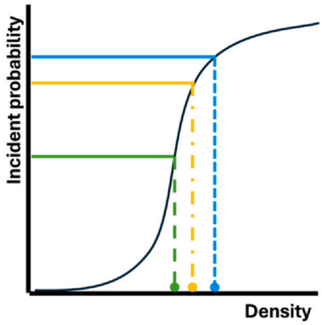

Fig. 6 Visualization of a cumulative distribution function (cdf) for incident probability.

more insight into the actual risk a crowd management organization is accepting. One could potentially derive these CDFs by means of simulation or laboratory studies.

2.5.3 Working example

To clarify how to derive metrics and thresholds, the rational presented above has been applied to an imaginary non-ticketed public event. Large crowds gather on a large square of $5000m^2$ for three days during this event. The square features a large music stage of $500m^2$ and 10 bars with an internal capacity of $141m^2$. 50.9 m of exit width is available in case of an evacuation. On the Friday of the event, 10% of the 16, 000 spectators (1, 600 P) of a local soccer club are expected to join the festivities after the match. Over the years, the police have learned that one can better facilitate their presence than trying to keep them out. Crowd monitoring systems are in place on the square and the routes leading up to the square.

Using the CRI framework, crowd incident risks are derived for this case with a relatively high incident probability, incident frequency and effect size, six of which are mentioned in Table 2. The crowd incident risks and resulting adverse crowding conditions are relatively diverse in nature. Next to normal operating conditions, potential adverse scenarios (e.g., fire on the square and complete evacuation of the square) have also been included. The rationale is that if these potential adverse scenarios occur, one should still be able to ensure the safety of the crowd, and crowding incidents should, therefore, also not occur during those conditions.

Accordingly, one or more metrics have been identified that quantify the identified adverse crowding conditions. Partly, these metrics are prescribed by national and municipal legislation. For example, the Dutch building decree mentions that it needs to be possible to evacuate a crowd from a building in 15 min. Even though a square is not a building, we can still use this number as a starting point. In addition, Daamen and Hoogendoorn (2010) find that at least 2.25 P/m/s can pass an exit with open doors. Together, these two facts can be used to identify that 103, 073 people can walk through the square's exits featuring 50.9 m of exit width. Partly, logic is adopted to derive these metrics. For instance, in the case of crowd turbulence, monitoring the local density might be more effective than the average density or total number of spectators, as Helbing and Mukerji (2012) showed that local force networks and pressure points arise in large crowds.

Table 2 Example calculation working example.

No.	Crowd incident risks	Metrics	Thresholds
1	Overcrowding of the square	Avg. density	$2P/m^2$
		Number of people	$4,\ 500 * 2 = 9,\ 000$ P
2	Evacuation of the square	Number of people	50.9m * 2.25 P/m/s * 15min = 103, 073P
3	Turbulence on the square	Max. density	$7P/m^2$
4	Entry soccer spectators	Number of people	$90,\ 000 - 1,\ 600 = 7,\ 400$ P
5	Ambulance on the square	Number of people	$(4,\ 500 - 50) * 2 = 8,\ 900$ P
6	Crowd reappears after rain	Number of people	$9,\ 000 - 141 * 10 * 2 = 6,\ 180$ P
	Final thresholds	Avg. density	$2P/m^2$
		Max. density	$7P/m^2$
		Number of people	6, 180 P (with rain)
		Number of people	7, 400 P (before soccer fans join)
		Number of people	8, 900 P (other)

In this working example, the Handboek Evenementenveiligheid (Stichting Evenementen Handboek, 2019), the Dutch building decree (Leefomgeving, 2025), and the works of (Daamen and Hoogendoorn, 2010) and (Helbing et al., 2007) have been utilized to derive relevant thresholds. The most restrictive thresholds should serve as thresholds for the crowd management systems on the square (see the last row of Table 2).

2.6 Risk mitigation directions

Note that the best mitigation strategy depends on the relationship between incident probability and incident effect size. If an incident is plotted on the top-left side of the graph, one can reduce the overall crowding risk most efficiently by reducing the impact of the incident. At the same time, if an incident is plotted on the lower-right side of the graph, it is better to mitigate the likelihood that the incident can occur. Consequently, the exact relationship between incident probability and effect size also hints at the most efficient crowding risk mitigation strategies.

Section 3 will present a framework to systematically design crowd management interventions. It is essential to remember while reading Section 3 that any intervention strategy has a main focus point in this respect. Interventions either decrease the incident probability or the incident effect size.

2.7 Synthesis on crowd risk identification and assessment methods

This section defined crowd safety as "people not being exposed to conditions in a crowd where they could lose physical control and/or lose consciousness" (van Schaik et al., 2024). Yet, it is often difficult to establish precisely when a situation moves from being safe to being unsafe. Therefore, in engineering and planning 'crowd incident risk' is often used to quantify safety.

Where risk is the product of (1) the probability that a crowd incident will occur, (2) the frequency that an incident occurs, and (3) the size of the impact (also called effect) of a crowd incident (Kinney and Wiruth, 1976). To quantify risk, several steps need to be taken:

- **Crowd Risk Identification** – The first step aims to identify crowd incident risks. The first one, drafted by (van Schaik et al., 2024), identifies crowd incident risks by systematically determining the adverse environmental conditions, adverse crowd conditions, crowd incidents, and the consequences of incidents. The second framework, proposed by Prof. Keith Still systematically identifies crowd incident risks using the phases of crowd behavior during a large-scale event and the primary influences of the environment on crowd behavior.

- **Ordering crowd incident risks** - The goal of this second step is to order the potential risks so that we can prioritize the allocation of resources to mitigate the biggest risks. By scoring the incident probability and effect size of potential crowd risks, one can quickly determine which risks are essential to monitor during crowd operation.
- **Quantifying crowd incident risks** - This third step aims to quantify crowd incident risks. To do so, each adverse crowd dynamics condition (crowd incident risk) is translated into a physical property of the crowd that can be monitored (the metric or KPI) and a value that identifies when the adverse crowd conditions are likely to occur (the threshold).

3. Designing crowd management intervention strategies

Drafting potential intervention strategies is the second step to manage a crowd. Yet, there are many ways in which one can intervene to mitigate crowd incident risks. So, how do you design an effective crowd incident risk mitigation strategy? Providing a comprehensive overview of intervention strategies in this chapter is ineffective, as every scenario requires a different intervention strategy.

In general, little research features methods to optimize a crowd's choice behavior or movement dynamics in pedestrian spaces or street networks. At the same time, many researchers have studied the processing of road traffic and which strategies can be applied to optimize the capacity of road networks. We can leverage their findings to optimize crowd choice behavior and movement dynamics.

Below, a systematic approach will be presented that was initially developed to optimize traffic flows but can also be used to design crowd management measures (or complete intervention strategies). Often, this systematic approach is referred to as the 'Golden principles of traffic (or crowd) management' as they form the core of most traffic management strategies around the globe.

Hoogendoorn et al. (2012) provided an overview of these golden principles for traffic management, being:

- Increase throughput
- Distribute traffic over the network
- Limit interactions
- Regulate the inflow of traffic

Fig. 7 visually depicts these strategies. Together, the four principles present a menu from which a crowd manager can pick and choose. The principles provide four distinct intervention design directions. It is up to the crowd manager to identify how a solution direction can be best achieved in a given context with a specific population. Distributing a crowd of habitual train passengers might require different tools than distributing a crowd of young teenagers on their way to see their idol for the first time.

Each of the four principles presents a lever a crowd manager can pull to prevent flow breakdown. Flow breakdown occurs when the demand at a cross-section is higher than the capacity of this cross-section (see Chapter 3 for an in-depth explanation of the capacity). That is, the available space is insufficient to accommodate the number of pedestrians who want to pass the cross section within a specific timeframe. The four principles allow the crowd manager to regulate the demand in the network so that the demand remains below the capacity of the infrastructure at any point in space and moment in time.

Below, each of the four golden principles for crowd management is discussed in more depth.

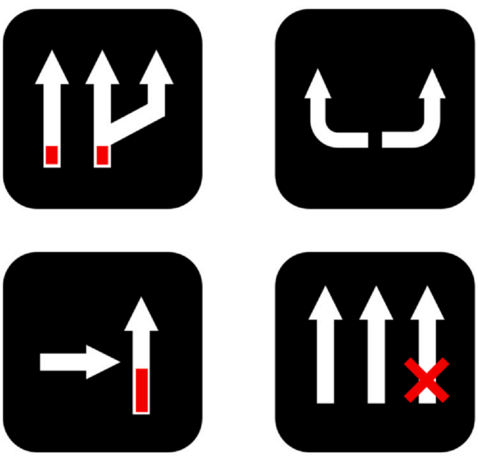

Fig. 7 Solution directions design interventions, from left to right, top to bottom: (A) increase throughput, (B) distribute traffic over the network, (C) limit interactions, (D) regulate inflow.

3.1 Principle 1: Increase throughput

Sudden changes in the layout of the infrastructure or obstacles along the route can lead to a local speed reductions and drops in capacity. If enough people are simultaneously present, speed reduction leads to continuously growing traffic jams that spread backward through the corridor and network. A stationary crowd that is pressured from behind becomes more dense over time, leading to potentially very dangerous pressure built-ups in the crowd. Move over, a backward moving jam can incur blockage of other corridors, leading to a complete standstill of the total pedestrian infrastructures.

Therefore, the most important crowd management principle is to prevent the blockage of other corridors in the network due to growing stationary crowds in each corridor. This means that if we allow a certain number of people to enter a corridor, we need to ensure that the same number of people can exit the corridor unhampered.

Even though this sounds simple, there are many reasons why the number of people who can enter and exit a corridor is not the same. The most obvious reason is the presence of an object in the corridor (e.g., pillars, dustbins, bicycle(fences), tables). Objects limits the effective width of the corridor. In addition to static objects in the corridor, the exit itself can also restrict people's movements (e.g., limited door width, revolving doors, gates) (Daamen and Hoogendoorn, 2010).

To increase the throughput, one needs to study the design of all corridors and intersections in the network in detail to identify the bottleneck locations. Accordingly, a solution needs to be designed for each of these bottleneck locations separately. The solution for a bottleneck location can be as simple as removing all dustbins at the narrowest part of the corridors or as complex as a complete redesign of the street layout to ensure a wider pedestrian path at the bottleneck locations. As the solutions are context-specific, this principle requires a crowd manager to identify all bottleneck locations and accordingly design fitting solutions for each bottleneck location based on their experience and logic.

3.2 Principle 2: Distribute the crowd

Often, the crowd is not equally distributed over the available space. As a result, it can be very busy in front of the stage, while it is very quiet at the main walking routes, or vice versa. Traffic flow theory identifies that walking speeds and throughput are highest when the density is low (see

Chapter 4 for a discussion on the fundamental relation between walking speed, density, and flow rate). Ensuring a more equal distribution of people ensures that the average density decreases. Consequently, the average walking speed increases, and the flow rate increases. The second principle aims to distribute the crowd over the available space.

A wide variety of measures can be applied to distribute a crowd over routes or spaces. Examples include, but are not limited to:

- using information messages and dynamic signage to alert pedestrians that there is a less-busy route available,
- improving the light design of the lesser-used route,
- distributing the attractions and food stands across routes so they appear to be equal with respect to amenities and
- strategically placing big screens near a stage to ensure pedestrians can see the events on stage from all sides of the event terrain.

3.3 Principle 3: Limit interactions

A third principle attempts to improve the throughput at critical locations within the pedestrian infrastructure. These critical locations can be both corridors and intersections. Yet, how do we increase throughput? Increasing pedestrian throughput is fairly difficult, as one cannot ask pedestrians to run through a corridor. So, what we mean in this case is that we ensure there are no external reasons for the flow to break down.

Flow can break down for several reasons. In general, flow breakdown is related to a decrease in the walking speed of pedestrians. Often, walking speeds drop when the complexity of the walking movements increases. When more interactions with other pedestrians are required, pedestrians need more time to process their options and, as a reaction, they limit their speed to give themselves time to react. Thus, proactively limiting the number of required interactions with other pedestrians limits the navigation tasks and increases the overall walking speed of pedestrian crowds. In a corridor, unraveling flows per direction is an often adopted solution. At intersections, unraveling flows is more complicated. In those cases, limiting the number of entering flows on the intersection limits complexity, for instance, by closing one of the four streets.

A second reason pedestrians' walking speed decreases is distraction. A sudden nice view, a pleasant shopping facade, a street act, or a nice vantage point on the music stage can cause a sudden drop in walking speed. By limiting the interaction between pedestrians and potential sources of entertainment, distraction is limited, and throughput increases. One example of a crowd management measure that aims to limit distraction is the placement of sight-disrupting fences near music stage areas at locations where one does not want pedestrians to stop and watch the show.

3.4 Principle 4: Regulate inflow

Sometimes, the first three strategies are simply insufficient, as crowd demand is higher than the total capacity of the pedestrian infrastructure. To ensure that flow breakdown does not occur, we must ensure that demand and supply remain balanced for as long as possible. The fourth traffic management strategy ensures that one limits the inflow of demand to the extent necessary to balance demand and supply and, where possible, also prevents overload in the area upstream of the area of risk.

For car traffic, inflow on busy traffic corridors is often regulated via access dosing installations (i.e., traffic lights). In the case of pedestrian inflow regulation, it is more challenging to use traffic lights and just ask people to stand in line to wait until the light goes green. However, scheduling demand using (free) tickets with time slots, dynamic gating systems, fast passes, and controlled fencing lines can sort a similar result. During the COVID-19 pandemic, time slots and predefined queues were often used to regulate crowding.

4. Automating crowd management

Yet, how do we know *when* and *where* the crowd incident risk is encroaching the thresholds we set, and we need to activate one or more elements of a crowd management plan? Crowd incident risk monitoring, from now on called crowd monitoring, allows crowd management professionals and public space planners to objectify the answer to the when and where questions and identify which interventions are most effective in a particular network and crowd state. The following section first briefly introduces the Quick scan that is adopted by crowd managers to quickly assess the state and safety of a pedestrian infrastructure (Section 4.1). Accordingly, Section 4.2 introduces the control loop for crowd management that (partly) automates the information gathering and Quick Scan process. Section 4.3 presents real-life applications of the crowd management control loop. This section closes with a brief synthesis of the content of this section (see Section 4.4).

4.1 Pedestrian infrastructure quick scan

Over the years, the author of this chapter has talked to a multitude of crowd management professionals and public space designers. Their stories are worrisome and exhilarating at the same time. What all their stories have in common is that they have a continuous loop of questions in their mind when monitoring and assessing the state of the crowd in a pedestrian infrastructure:

- Who is present in the venue or public space, and who is going to be present in the near future?
- Where are they, how are they distributed now and in the near future?
- What is their mood?
- What activities are they performing and will they be performing in the near future?
- Which routes are they following or will they choose in the near future?

Crowd management professionals combine the answers to this first list of questions into an approximate crowd-state estimation and crowd-state prediction. The current and most likely future crowd states are accordingly used to answer another three questions:

- Are the individuals that make up the crowd safe right now and in the near future?
- Will they stay safe in the near future without proactive intervention?
- If they are not or will not be safe, which interventions should be applied to most effectively keep them safe in the near future?

The combined answers to the Quick Scan allow crowd managers to identify the risks that are most likely to be operationalized. During the preparation of the operation and the actual operations of a pedestrian space, the crowd risk question tree is run continuously.

The Quick Scan puts a lot of pressure on crowd managers. Raw data from lots of different sources and featuring a wide variety of formats needs to be translated into actionable information on the fly. This information accordingly needs to be interpreted and assessed. Only when all information is evaluated can the crowd manager determine whether the state of the pedestrian infrastructure has changed since the last Quick Scan.

4.2 Crowd management systems

Crowd Management Systems (CMS) can support crowd management professionals with their monitoring, estimation, risk identification and risk assessment tasks. CM systems are a type of Intelligent transportation systems (ITS). An ITS is ‘an advanced application which aims to provide innovative services relating to different modes of transport and traffic management and enable users to be better informed and make safer, more coordinated, and ‘smarter’ use of transport networks.’ (Mahmood et al., 2022). In layperson’s terms, ITS is the adoption of innovative technology to improve the performance of a traffic network or piece of infrastructure.

Most people have experienced the result of ITS applications for crowd management purposes. Examples include, but are not limited to, ticket gates with variable operating speed, light systems that are activated by the presence of people, dynamic routing information in train stations, and dynamic evacuation signage. These ITS systems vary heavily in physical presentation, the required intelligence, and the type of choice behavior and movement dynamics they influence. The commonality between all these systems is that they provide users with insights to optimize their decision-making.

ITS is a broad concept, as every measure that uses innovative technologies to improve a traffic system might work. In this section, we will focus on one category of ITS: Crowd Management Systems (CMS). CMSs aim to influence traffic flows (i.e., crowds) using real-time data to increase the system’s performance from the perspective of prevailing (and potentially varying) policy objectives.

Fig. 8 shows a conceptual diagram of the control loop for crowd management that forms the foundation of most operational CMSs. A control loop comprises five action elements: sensing, state estimation, state

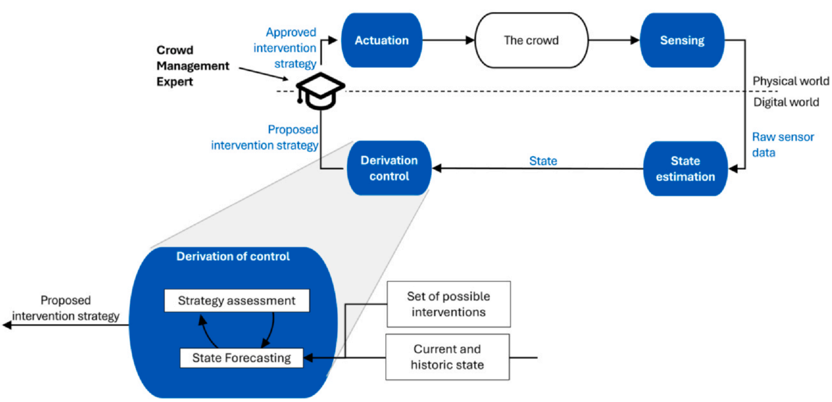

Fig. 8 A schematic overview of an intelligent transportation system for crowd management and control, originally developed by Flurin Hänseler.

forecasting, strategy assessment, and actuation (advise). Here, the current crowd dynamics, the pedestrian infrastructure layout, current and future demand on the boundaries of the pedestrian infrastructure, and the set of potential CM interventions are inputs to the control loop at various stages.

Underneath, we will briefly introduce all five action elements.

4.2.1 Sensing

CMSs make use of digital sensors to gather information regarding the choice behavior and movement dynamics of crowds in pedestrian infrastructures. Digital sensors record the unfolding of events on the street (e.g., smart camera) or digital reality (i.e., social media). They translate the messages, choices, and movement dynamics of people from a physical presence into a digital signal. In the case of a smart camera supported with computer vision software, the input is a pedestrian moving through a street, and the output of the sensor is a predefined format that records the position of an object in a given coordinate system.

Chapter 3 of this book provides a comprehensive overview of crowd monitoring techniques. The reader is referred to this chapter to uncover the potential of pedestrian sensing techniques. What is essential to realize is that the characteristics of monitoring techniques, and as such, the insights one can gather using monitoring techniques, are pretty diverse and rather specific. Therefore, matching the monitoring techniques with the required insights is essential. For example, if one needs to know via which routes flows through your network are moving through the network between origin and destination, RFID and WiFi are more practical, while smart camera systems are more useful for flow counting.

In many cases, the choice for a specific monitoring technique is governed by ethical and regulatory restrictions to safeguard the privacy of individuals, the cost price of the monitoring network installation and operation, and environmental conditions. In addition, also practice often sets the conditions for the monitoring technique, e.g., height vantage point, light conditions, availability of power. Besides that, safeguarding crowd monitoring equipment against vandalism is a vital requirement for 24/7 monitoring techniques.

4.2.2 State estimation

The second element of the control loop for crowd management is a state estimator, whose objective is to identify the current state of the system we are trying to manage. Traffic engineering concepts are often used to derive a more comprehensive image of the system's state based on sensor readings. Even though the state estimator's output depends heavily on CMSs' purpose, often, the velocity, density, and flow rate of pedestrian crowds are estimated to infer a fundamental diagram. The reader is referred to Chapter 4 for a more in-depth discussion on the pedestrian fundamental diagram.

Sensor data can be leveraged in multiple ways to determine a crowd state. Firstly, one can directly use the data of one sensor to determine one or more state variables for a particular location. Secondly, one can use multiple types of sensors to determine multiple state variables for a particular location utilizing so-called data fusion techniques (e.g., Daamen et al., 2016; Yaseen et al., 2013). The idea of data fusion is that the strengths of each sensor type can be leveraged to enhance the overall insights one can derive from the combined sensor network. For instance, using a limited set of expensive smart cameras to validate the measurements of a wide-spread network of WiFi sensors. Lastly, one can use multiple types of sensors at multiple locations to identify the state of a location somewhere in the middle where one cannot directly measure the state (Duives et al., 2018).

In state estimation, observability is an essential concept. In essence, one needs to be able to reconstruct the state from the collected data. Often, boundary conditions apply under which we can 'observe' the state. For instance, we can only determine the average speed of a pedestrian if we can distinguish the trajectories of all moving objects in the field of view of the camera. In the case of the crowded square, we can only determine the current density utilizing entrance flow counters if the density at a previous point in time is known and a continuous data stream exists from that moment onward.

Over the years, various state estimation algorithms have been presented. Most of these techniques leverage one or more sensing techniques to identify the number of individuals present within the sensor's field of view. (Khan et al., 2023) provides a nice overview of the state-of-the-art crowd-counting techniques and (Singh et al., 2021) an overview of the state-of-the-art crowd-monitoring techniques. Both show that conventional crowd monitoring systems mainly rely on computer vision approaches, which have some nasty side effects. First, one only derives information inside the camera's field of view, leaving the analysis blind to what happens just outside the field of view. Secondly, most camera-based systems do not preserve the privacy of the pedestrians recorded by the camera as data is transmitted to a cloud before the images are analyzed.

Infrequently, researchers have attempted to combine the measurements of multiple sensors to derive insights into other parts of the pedestrian network. Yet, (Duives et al., 2018) shows that one should be careful when combing the measurements to determine a crowd state outside the sensors' direct field of view. Even a little bit of systematic noise in sensors can heavily skew the results. So much so that the resulting state estimation cannot be trusted in the operation anymore.

The need for continuous state estimation and the issues regarding noisy measurements are not new phenomena. Traffic engineers have been developing techniques to deal with these issues for several decades. Some example applications of these traffic engineering methods for crowd management purposes can be found in (Daamen et al., 2016; Hoogendoorn et al., 2016), and (Duives et al., 2017). The first compares the capabilities of smart cameras, WiFi sensors, and GPS sensors to identify the state at a large-scale event. The second adopts statistical techniques to determine the average travel time based on noisy WiFi measurements. The latter uses an established traffic engineering method to derive the state between sensor locations. In addition, (Duives et al., 2020) presents a traffic engineering-informed data-fusion technique that can leverage the best characteristics of multiple systems to derive a better state estimation.

More recently, we have seen that big data analysis techniques, particularly machine learning approaches, have been leveraged to improve pedestrian state estimation. For instance, (Jiang et al., 2019) uses encoder-decoder networks to improve crowd counting and density estimation. As crowd-monitoring data becomes more readily available in the coming years, we expect many more exciting machine-learning techniques to be presented.

4.2.3 State prediction

The current state is often insufficient to understand the risks a crowd poses. One needs to understand how the current state is going to evolve. For instance, a density of 2 pedestrians per square meter can be sustained for an extended period of time on a square without issues. Yet, this same density might be undesirable if one knows that 40.000 soccer spectators will join the square in the next 15 min. Understanding how the state of the crowd will evolve is essential to identifying whether or not crowd management measures need to be deployed now or in the near future.

In essence, any pedestrian simulation model can be used to predict the future states of a pedestrian crowd. (Mai et al., 2025) and (Liu et al., 2021) show that data-driven machine learning algorithms can also be trained for state-prediction purposes. Chapters 6 and 7 have presented many interesting microscopic and macroscopic pedestrian simulation models that could do the trick. At the same time, the machine learning algorithms are developing so quickly at this moment that the reader is advised to review the latest AI-based state prediction algorithms online. Therefore, this chapter will not elaborate in-depth on state prediction techniques.

Yet, what is essential to realize is that a good state prediction is not deterministic. Reality is generally messy. We often do not know precisely what the system's current state is or what the exact boundary conditions are now and in the future. Whenever performing a crowd state prediction for a CMS, the noise within the inputs must be accounted for in the final state prediction. As a result, a large set of scenarios will need to be simulated to infer the system's most likely future state(s).

Most current crowd simulation packages struggle to simulate large crowd scenarios faster than real time. Potentially, an entirely new set of (hybrid) macroscopic pedestrian simulation models is required to alleviate this issue. However, in the meantime, most current pedestrian simulation models can not be used in the CMSs state prediction module. Godoy (2020) presents a preliminary method to circumvent most current simulation models' computational burden. They design a scenario database, which features many different scenarios for the most problematic bottlenecks within a pedestrian infrastructure. Accordingly, the state prediction module only needs to select the most relevant scenario(s) from the database during runtime, thus reducing the prediction latency.

4.2.4 Derivation of control

The next step in a CMS is to identify what actions one can take to optimize the performance of the system. This so-called controller aims to determine the intervention strategy that moves the system towards the design objective of the system. In the case of a CMS, the design objectives are often related to safety, efficiency, or service and the system is the pedestrian infrastructure.

Often, a vast array of potential control options is available within a pedestrian infrastructure. To mitigate the crowding incident risks on a crowded square, one can use various crowd management measures to decrease the inflow of new visitors, among other things, destination advice (i.e., 'do not go there'), physical blockages of streets, Instagram messages ('Look it is SUPER crowded here'). Moreover, there are also various methods to invite people to leave an overcrowded square, such as an annoying sound, staff members asking people to leave, and closing shops or bars on the square.

Consequently, the question is, 'What combination of potential crowd management actions best fits our crowd management objectives?'. In mathematics, this translates to equation (1), where $\overrightarrow{u}(t)$ denotes the setting of the actuators, and U is a function of the current state of the system. In essence, the equation states that the control strategy is a function of the current state of the system and some other factors. This is a combinatorial problem that explodes quickly.

$$\overrightarrow{u}(t) = U(\hat{x}(t), \ldots) \tag{1}$$

In essence, three types of approaches have been presented to specify the function U in the controller block:

- **Rule-based systems** – These systems feature one or more IF., THEN. rules. For example, if the crowd density on a platform is higher than 2 P/m/s, the escalators are stopped. Jointly, the set of rules describes all the possible states in the system and the best response given to each state. The rule-based system works well for simple crowd management scenarios where the set of possible states and the number of actuators are limited.
- **Heuristic approaches** – In these heuristic approaches, the controller is expressed in a functional form (e.g., $u(t) = K_1 e(t) + K_2 e'(t)$ where $e(t) = x(t) - x^*$ quantifies the difference between the desires state x^* and the current state $x(t)$). This means that the strength of the actuation signal (intervention) is via some formula related to the characteristics of the crowd state and the desired state. For instance, the speed of the ticket gate decreases linearly when the density on the platform increases. Accordingly, the control strategy reacts to deviations of the current state from the desired state. Heuristic approaches are relatively flexible and simple to design. However, in the case of larger, more complex crowd management operations, the design quickly becomes more complex, and optimality cannot be guaranteed.
- **Model Predictive Control (MPC) approaches** – An MPC uses (simulated) predictions of the future state of the system to determine the best control strategy for the current time (see Eq. (2)–(4) for the mathematical formulation of the problem). In essence, MPCs derive the best control strategy by rapidly simulating a sequence of the future states for a wide array of potential intervention strategies and accordingly picking the

best intervention strategy from the simulated options using an objective function that quantifies the performance of the system using one or more KPIs. MPC is a generic mathematical concept that can be applied as long as one can determine a prediction model $f(t, x(t), u(t))$, one can model the impact of the control signal $u(t)$ and one can express the performance of the system in terms of an objective function J. Hänseler and Hoogendoorn (2018) presents an interesting implementation of an MPC for the actuation of the escalators leading toward the platforms of metro stations. The computational burden of the MPC is quite extensive. Yet, especially in more complex crowd management scenarios with various actuator strategies, the MPC outperforms the other two control approaches.

$$u^*_{[t,t+H)} = \arg\min J\left(u_{[t,t+H)}|x(t)\right) \tag{2}$$

$$J = \sum_{s=t}^{t+H} L(s,\ x(s),\ u(s)) \tag{3}$$

$$x(t+\delta t) = f(t,\ x(t),\ u(t)) \tag{4}$$

4.2.5 Actuation of control

At this moment, one has already inferred the best intervention strategy for the current state of the crowd in the venue using one of the possible controller blocks. The last step of the dynamic crowd management system is the actual operationalization of the control strategy by means of actuators. Here, the word actuator refers to any object or entity that can be used to manage the crowd. Examples thereof are gates, message signs, and security personnel. The words intervention strategy refer to a discrete set of actuators that are simultaneously operationalized at a given moment in time.

In the case of digital actuators, the actuator settings can be digitally communicated directly to the actuators. Examples of digital actuators are lights, escalators, and signage systems. In the case of human actuators, first, a translation of the digital actuator strategy into a human-understandable instruction (e.g., written or spoken text) is required. The more complex the actuation strategy, the more time-consuming the translation of the instructions into a human-understandable format will be.

Even though this step in the CMS seems trivial, in practice, it often turns out to be the most challenging step of the process. It takes time to operationalize actuator strategies. Just imagine how many intermediate steps need to be taken to operationalize a fence line at a festival. First, security guards need to be instructed to move to the identified location. Accordingly, they need to move to the area. Then, the fences need to be closed, and people need to be redirected. This is all under the assumption that the fences were already in place and did not need to be gathered at a different location first. Consequently, even if everyone and everything is in place, it takes time to operationalize most actuator strategies.

4.3 Crowd monitoring applications

Currently, few CMSs are operational that actually complete the entire control loop for crowd management. That is, they recommend (or even apply) interventions using information that is automatically derived from sensor networks. More frequently, CMSs only feature the sensoring, state estimation, and state prediction elements of the control loop. This is because the prediction of rapidly changing pedestrian states remains very tricky in this day and age. Such a CMS that is only used to sense, estimate the current state, and predict a future crowd state without providing advice regarding the most effective intervention strategy can be seen as a crowd state monitoring system or a crowd incident risk monitoring system.

Most CMSs depict a wide array of variables on a digital dashboard. Accordingly, it is up to the data analyst to translate the data into actionable information. The analyst has to translate the data because there is not yet a quantitative relationship between the crowd incident risk and the crowd state variables. Consequently, we can only use the second-best thing to identify the crowd incident risk, namely, quantifying the crowd state variables.

Relevant state variables often used in crowd incident risk monitoring systems include walking speed, density, flow rate, the number of people in an area, travel time (delay), and activity time. Which of these is most relevant depends on the scenario. For example, the number of people in the area might be most appropriate for a square with a maximum evacuation capacity, while the density and flow rate might be more suitable for a metro station platform.

Crowd risk monitoring systems are applied across the globe. Examples of existing CMSs are the Argaleo's digital twin of Scheveningen (Argaleo, 2025), the OMDt (Mobility Innovation Centre Delft, 2025), the CMS featured in Mecca (Aldahawi, 2021), the CMSs of the London Underground (Nguyen et al., 2019) and DCM's crowd monitoring system operational at Sydney Olympic Park (DCM, 2025). Many more CMSs are operational at this moment.

To showcase the possibilities of CMSs, two Dutch applications are presented in more detail below.

4.3.1 CMS example 1: The outdoor mobility digital twin

In 2020, a new virus named SARS-CoV-2 spread rapidly across the globe. The health impact of the accompanying disease, COVID-19, was immense, featuring severe risks of hospitalization and even death for a large part of the population. Until today, more than 7 million people have died as a consequence of COVID-19 (World Health Organization, 2025).

Scientists soon learned that this airborne virus spread from person to person via droplets and aerosoles (very small moisture particles in the air) that are produced during any respiratory action (e.g., breathing, sneezing, singing, shouting). They found that the 'dangerous' droplets can reach a distance of 1.5 m (Atamer Balkan et al., 2024). So, to limit virus transmission, unaffiliated persons were asked to keep a 1.5 m distance at all times. In addition, stringent lockdowns were instigated in various countries (i.e., prolonged closure of schools, restaurants, theatres, and shops). These interventions worked well to limit transmission but also had a significant impact on the functioning of society while the world was awaiting the arrival of the first vaccines.

As SARS-CoV-2 is an airborne virus, keeping distance was essential to limiting disease spread while opening up society again. Consequently, new ways to manage crowd density at far lower levels than before were required to open up society again. TU Delft developed an ITS system named the Outdoor Monitoring Digital twin to manage crowds under physical distancing restrictions (Mobility Innovation Centre Delft, 2025). Underneath, a brief description of the implementation of this Dynamic Crowd Management system is provided. The elements of the control loop for crowd management are used as a guiding rod.

Crowd management objective: The main objective of the OMDt was to limit the COVID-19 transmission risk by limiting the crowd density on campus at all times. Thus, the density at the campus needs to remain below $1/(1.52) = 0.44P/m^2$.

Sensing: A vast sensor network was installed at the campus featuring sophisticated depth sensors, radar, and WiFi sensors. The depth sensors identify the trajectories of all moving objects in the field of view and determine the distance between all objects. The radar sensors determine the flow rate and speed at specific cross-sections. The WiFi sensors were used to compute the route splits in the sensor network. Please note that the WiFi sensors are currently disabled to ensure the privacy of campus visitors.

State estimation: For this crowd management goal, the inputs from the depth sensors have proven especially useful, as these sensors provided insights into the number of objects in the field of view, as well as the distances between the objects. The global density, flow rate, and minimum distance between individuals could be computed based on these two inputs. Where the first gives information on the overall compliance to the 1.5-meter physical distance restriction, the latter gives information on the compliance of each individual in the crowd. If all people stand in the same corner, the global density can still be within bounds, but the individual distances are far below the required threshold of 1.5 m.

State forecasting: Based on the current state, a neural network was derived that provides insights into the predicted flows and densities on campus for the coming days. This allowed the controller to determine the future state of the campus.

Actuation and control: In this example, only the first two elements of the CMS have been developed, as the impact of the crowd management measures was unknown and, thus, uncontrollable. A set of KPIs was needed to assess the system's future state. Duives, van Schaik, and Hoogendoorn have developed a framework to identify the capacity and monitor the Level of Service under COVID-19 restrictions (Duives et al. under revision). This framework uses three metrics: the flow rate, the density, and the number of 'risky' interactions in the field of view. The information regarding the future state of the system was directly sent to the crowd management professionals. Based on the current and most likely future state of the system (in relation to the COVID-19 KPIs), crowd management measures were deployed at specific locations and periods of time.

4.3.2 CMS example 2: Crowd management during Kingsday in Emmen

Kingsday is a national event in the Netherlands during which Dutch citizens celebrate the king's birthday. During the day, large open-access music events are organized in almost every municipality across the country. Due to the open nature of the events, it is challenging to estimate the number of visitors who attend these festivities in a given year. Consequently, many cities apply CMSs to monitor the crowding risks during Kingsday better.

Crowd management objective: The crowd management objective of the Kingsday event in Emmen was to limit the crowding risks on a large square in the city center. To the authors' knowledge, no formal thresholds were defined. Yet, an informal threshold of a density of $2P/m^2$ is often applied during most Dutch events.

Sensing: 15 standalone sensors of the company CrowdScan were used to determine the average crowding levels and density on a square of 100 m by 50 m. Even though these sensors are quite sensitive to the presence of cars and big obstacles, they work reasonably well in car-free environments. The data from CrowdScan was linked in one Digital Twin environment of the company Argaleo which featured open data regarding real time traffic information, the occupancy rate of parking lots, weather forecasts, the current state of public transit operations, and information featuring the registered use of buildings.

State estimation: In this case, especially the density metric was used to determine the crowding level on the square. This metric was directly derived from the CrowdScan system. No additional state estimation software was used besides the internal software of the CrowdScan system.

State forecasting: No state forecasting algorithms were applied in this operationalization of the Digital Twin environment.

Actuation and control: Based on the data provided in the Digital Twin environment, the crowd management team in control of the public events during Kingsday in Emmen determined which crowd management interventions were activated at what time. As such, the CMS acted as a crowd incident risk monitoring system.

4.4 Synthesis on the automation of crowd management

This section identified that crowd management professionals use a Quick Scan to identify the risks that are most likely to be operationalized. During the preparation of the operation and the actual operations of a pedestrian space, the Quick Scan is run continuously, which puts a lot of pressure on a crowd manager due to the need to gather, translate, and interpret vast amounts of data in a short period of time.

Crowd Management Systems (CMS) can support crowd management professionals with their monitoring, estimation, and risk assessment tasks. CMSs aim to influence traffic flows (i.e., crowds) using real-time data to increase the system's performance from the perspective of prevailing (and potentially varying) policy objectives.

Any CMS can be described using the control loop for crowd management. We showed that the control loop for crowd management comprises five action elements: sensing, state estimation, state forecasting, strategy assessment, and actuation. Here, crowd dynamics, the network layout, current and future demand on the boundaries of the pedestrian infrastructure, and the set of potential CM interventions are inputs to the CMS.

CMSs are applied across the globe. Yet, few operational CMSs actually complete the entire control loop for crowd management. Most frequently, CMSs only feature the sensoring, state estimation, and state prediction elements of the control loop. Up to date, most CMSs depict a wide array of variables on a digital dashboard and function more like a crowd monitoring system than a full-fledged CMS. Relevant state variables often used in CMSs include walking speed, density, flow rate, the number of people in an area, travel time (delay), and activity time.

5. Practical notes on the operationalization of crowd management

The previous sections have detailed how to identify potential crowd incident risks, how to design crowd management interventions, and how to set up monitoring systems to monitor these risks. When applied correctly, these actions result in a robust crowd management operation that systematically monitor and mitigates potential crowd incident risks.

The following section provides some miscellaneous remarks with respect to the operationalization of these crowd management plans and systems.

5.1 Crowd management at different time scales

The literature suggests that crowd management is predominantly applied at short timescales (i.e., hours, days, weekends). This is certainly not the case. Crowd management starts as soon as the urban planner or architect draws the first sketches of a new neighborhood or pedestrian infrastructure (e.g., train station, street, or university building). Many crowding issues can be solved far easier and cheaper at the design stage than later during the operational phase of pedestrian infrastructures.

Consequently, it is essential to realize that crowd management works with two timescales. In the short term, one optimizes the crowds' behavior given the current physical restrictions of the infrastructure. In the long term, one optimizes the infrastructure design to better fit the crowds' desired choice behavior and movement dynamics. Only when accounting for both short- and long-term crowd management processes can one develop pedestrian infrastructures that intrinsically empower pedestrians to make the right choices and ensure the physical, social, and mental safety of all pedestrians within the infrastructure.

5.2 Human in the loop

A comprehensive CMS can function without any human interference. These CMSs can sense, estimate, and predict the system's future state, derive the actuator, and deploy the actuator strategy themselves. However, given the potential impact of the actuator strategies, it is questionable whether fully automated CMSs are desirable.

What if a sensor is faulty (e.g., very low-density readings because umbrellas are not identified as humans)? What if certain pieces of information cannot be processed by the system (e.g., a demonstration with violent individuals moving through the city streets)? What if the actuator strategy manages the situation within its span of control brilliantly but forgets about the outside world (e.g., massive queues in front of the metro station)? What if the external effects of a CMS are not recognized because they were not included in the original design (e.g., the CMS only accounts for loss of efficiency, but not crowd pressure)? A fully automated CMS might control the wrong direction in all those cases. That is, not intervening when interventions are necessary, or vice versa.

A human in the loop who performs a final check on any actuator strategy can alleviate most of these issues. In essence, the human checks that the CMS has not missed any vital information relevant to the current scenario and can override the system if the circumstances require it. This creates an essential fail-safe for any situation where the CMS the lacks data and/or rules to correctly manage the situation.

5.3 Crowd management legislation & guidelines

In most countries worldwide, there are laws and guidelines concerning crowd management operations. Often, building decrees feature guidelines concerning the evacuation capacity of doors, corridors, and stairs. The Guide to Safety at Sports Grounds (also known as the Green Guide - (Sports Grounds Safety Authority, 2018)), the Dutch Handboek Evenementenveiligheid (Stichting Evenementen Handboek, 2019), and DIN18009-2 (German Institute for Standardization, 2022) are a few exceptions to this rule.

Due to the limited formal legislation and guidelines, using the latest insights regarding crowd dynamics and human factors to determine the relevant key performance indicators and thresholds when developing crowd management plans and operationalizing CMSs is essential. In addition, it is essential to keep questioning whether the current guidelines are sufficient for any particular crowd management context as legislation is not specifically designed to be used to assess (outdoor) pedestrian infrastructures.

6. The future of crowd management

The field of crowd management evolves quickly. The increase of computation power, the introduction of new sensing technologies, and the development of new machine learning techniques will rapidly change the field as we know it. Underneath, some challenges for the crowd management field in the years to come have been formulated.

6.1 The impact of crowd management measures

Most CMS currently function as a crowd monitoring system or crowd incident risk monitoring system. They feature state-of-the-art sensing equipment and state estimation software but have limited predictive capabilities and do not feature controllers that can provide actuator strategy advice.

The development of comprehensive CMSs is currently stuck at the state prediction phase. The development of state prediction algorithms for crowds is hampered by the fact that few insights exist regarding the impact of crowd management actuator strategies on pedestrian choice behavior and movement dynamics. Even if one has the computational power to simulate the unfolding of crowd dynamics quickly, one cannot simulate the impact of crowd management actuator strategies in these future scenarios. One of the significant challenges in the field of crowd management is to develop the necessary empirical insights that will enable the prediction of relevant future crowding scenarios.

6.2 Developing standardized crowd safety KPIs

Another recently started discussion entails the question: 'When is a pedestrian safe?' Even though the question sounds trivial, its answer is far from trivial. What key performance indicators and thresholds should be applied in which context? Some preliminary suggestions regarding metrics and thresholds have recently been presented by (van Schaik et al., 2024). Yet, a lot more research is required to derive a comprehensive set of KPIs and accompanying thresholds, given all the externalities that have an effect on these thresholds. A better understanding of the relationship between crowd dynamics variables (e.g., speed, density, flow rate, and travel time) and crowd incident risk is required. Besides that, the measurement of these KPIs needs to be standardized as much as possible to ensure that all crowd management organizations monitor and interpret the same metrics the same way.

6.3 Crowd monitoring and privacy

More and more frequently, CMSs are applied, which use smart cameras featuring computer vision software. Even though it is possible to design computer vision algorithms that intrinsically protect citizens' privacy, many current smart camera systems do not implement privacy-preserving algorithms.

It is essential that we design and operationalize CMSs that protect the fundamental rights of EU citizens. Consequently, when operationalizing a new CMS, it is essential to question companies that provide sensor equipment regarding how they protect the right to privacy. Moreover, it is essential to check that the right to privacy can still be guaranteed when data fusion algorithms that stack data from multiple sources are adopted. New privacy-preserving data-fusion algorithms can support the development of genuinely Responsible CMSs.

6.4 Responsible AI in crowd management?

Machine learning algorithms, a substream of artificial intelligence, are quickly changing the world as we know it. They are also expected to change how we currently perform crowd management. For starters, advances in sensing equipment are expected due to the enhanced capabilities of computer vision algorithms. In addition, Graph Artificial Neural networks (GANN), Reinforcement Learning (RL) models, and Large Language Models (LLMs) are expected to change how we assess the current crowd state and predict future crowd states.

Most state-of-the-art deep learning algorithms currently operate as a black box. The inputs and outputs are known, but the incredibly large number of parameters limits the interpretability (i.e., how the AI model makes the prediction) and explainability (i.e., why the model makes a prediction) of most AI models.

As crowd management decisions directly impact human lives, it is essential that we start developing specialist machine learning algorithms for crowd management purposes that are '*responsible*'. In particular, we need algorithms that align with our values, legal standards and ethical principles, and workflows that mitigate the risks and adverse outcomes that are associated with the use of AI.

7. Synthesis

This chapter provided practical guidelines for designing effective crowd management solutions. When used in unison, these guidelines answer the when, where, and how questions formulated above. These guidelines comprise three elements: (1) crowd risk identification and assessment, (2) crowd management interventions, and (3) automating crowd monitoring and management.

The first set of guidelines showed that to quantify risk several steps need to be taken:

- **Crowd Risk Identification** – The systematic identification of failure routes (and as such incident risks), for instance, using the CRI or DIM-ICE frameworks.
- **Ordering crowd incident risks** – The ordering of the potential risks to allow for prioritization of resources to mitigate the most significant risks.
- **Quantifying crowd incident risks** – The derivation of physical properties of the crowd that can be monitored utilizing a metric and metric threshold.

Accordingly, this chapter presented a systematic approach developed for optimizing traffic flows but can also be used to design crowd management measures (or intervention strategies), which were referred to as the 'Golden principles of traffic (or crowd) management'. These four principles are: (1) increase throughput, (2) distribute traffic over the network, (3) limit interactions, and (4) regulate traffic inflow. Together, the four principles present a menu from which a crowd manager can pick and choose. The principles provide solution directions. It is up to the crowd manager to identify how a solution direction can be best achieved in a given context with a specific population.

In the design and operation phase, crowd management professionals use a Quick Scan to identify the risks that are most likely to arise. Crowd Management Systems (CMS) can support crowd management professionals in this daunting task. CMSs aim to influence traffic flows (i.e., crowds) using real-time data to increase the system's performance from the perspective of prevailing (and potentially varying) policy objectives.

Any CMS can be described using the control loop for crowd management. We showed that the control loop for crowd management comprises five action elements: sensing, state estimation, state forecasting, strategy assessment, and actuation. Here, crowd dynamics, the network layout, current and future demand on the boundaries of the pedestrian infrastructure, and the set of potential CM interventions are inputs to the CMS.

These CMSs are applied across the globe, and the field of crowd management is evolving quickly. This also produces a set of challenges for the field.

Firstly, new empirical insights are required to predict relevant future crowding scenarios. Secondly, a better understanding of the impact of metrics and thresholds is essential to allow for the development of more robust and reliable CMSs. Thirdly, to protect the fundamental rights of EU citizens, new types of CMSs that are transparent, explainable, and minimize their data consumption are required. Lastly, to mitigate the risks and adverse outcomes associated with using AI algorithms, new algorithms that align with our societies' values are needed.

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Ethics

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CRediT authorship contribution statement

Dorine C. Duives: Conceptualization, Methodology, Formal analysis, Data curation, Writing - Original Draft, Writing - Review & Editing, Funding Acquisition, Supervision.

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